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Title: FINAL REPORT IC PROJECT w17_seismicsources “ Walking the road from impacts to seismic sources for celestial bodies”

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FINAL REPORT IC PROJECT w17_seismicsources " Walking the road from impacts to seismic sources for celestial bodies"

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Scientific Impact. The goal of this project is to develop new LANL modeling capabilities for impacts. Our approach is based on HOSS (Hybrid Optimization Software Suite), an unique numerical capability combining discrete and finite element modeling. Further developments were made during this project: Lagrangian and Eulerian domains have been coupled together combined with a technology accommodating large strain deformation. We have now a numerical tool with unique capability which may be the best solution to model impact on planets covered with regolith, a very unconsolidated type of soil created by the disintegration of bedrock by repeated cratering, radiation exposure and erosion processes (wind). We are part of the Insight Science Team, actively participating into the Impact Working Group and there are no such capability in that international team. We are now teaming up with Pr. Lognonné, the lead-PI of the SEIS instrument, the Insight seismometer that is currently the only seismometer performing on another planet than Earth, to continue supporting Insight Science Mission. An undergraduate student of Pr. Lognonné has started worked with us with the plan to do a full Ph.D. project in the future.
During this IC project, a lot of effort was spent on the development and validation and verification of the new modeling capabilities. We also have some scientific: (1) Implementation of a new material model which can handle unconsolidated material such as soil, and sedimentary basin filling. The new model has required a redefinition of deformation kinematics used in the finite element formulation in order to accommodate the very large levels of deformation involved when modeling unconsolidated materials. This solution offers a clear advantage over other Lagrangian hydrodynamic codes as they are limited in the amount of deformation they can properly capture. In concert with the updated element, a new material model that accommodates phase changes by utilizing the renown Tillotson Equation Of State (EOS) has been implemented. Just as important, to further accommodate the needed physics the HOSS code is well underway to being upgraded to have a fluid-structure interaction (FSI) module - This module will allow us to simulate impact and cratering processes inp laces with atmosphere, incorporate the effects of fluid flow through cracks, provide a method that allows donation of a failed Lagrangian element onto an underlying Eulerian grid (phase changes, rubblization,etc.). Of note, this FSI will be submitted for a patent application as no other FDEM code in the world has this capability. (2) V&V (Validation & Verification) and material model calibration for unconsolidated materials: We are performing V&V for different nuclear events that were performed in sediments and are well documented. It was recommended to us by our XCP collaborators to conduct a benchmark exercise proposed by Pierazzo et al. (2008) which is well recognized by the impact scientific community.(3) V&V with JPL experiments conducted at the Ames Vertical Gun Range of impacts on sand and pumice. (4) Establishment of scattering models for the Moon: Due the heterogeneous and dry nature of the crust of the Moon, it is the place of extreme scattering of the seismic waves using the spectral Element method. This work

has mainly involved the search of different algorithms to create perturbations of the elastic properties which reproduces observed scattering in seismic records. This work was presented at the 2018 Seismological Society of America meeting.(5) Modeling of the seismic waves generated by the Chelyabinsk bolide. This work was mainly performed by a Ph.D. student at the Institut de Physique du Globe. He uses normal mode modeling in an Earth model combining solid Earth and atmosphere to invert he seismic energy delivered in the atmosphere by the bolide. This result was compared to a spectral element modeling (SEM) in a solid Earth only model (no atmosphere). The findings are that the seismic records of the bolide show a clear signature of the local 3D elastic structure of the crust, as well as, directivity effects related to the trajectory of the bolide. A paper has been accepted in Space Review Letter.

Programmatic impact.

Our work aims to advance general knowledge about planetary evolution and the appearance of life. Data that can shed light on these topics is expected to be preserved into the deepest parts of bodies of our Solar system, and NASA is searching for technologies that can help unravel this information. Our goal is to improve impact seismology modeling which can be used to image internal structure from the records of impacts onp lanets/moons. Such technology can also be used to estimate the on-site natural resources and to aid in our pursuit to find future habitable planets or life outside Earth, and, in such, be instrumental in strengthening the leadership of US research and DOE mission on sustainable energy.

Our work has obviously direct implications on supporting NASA mission, including future Discovery missions into environments with atmosphere such as Mars (thin atmosphere), with ocean (Europa) and/or even advance our modeling capability to assess the threat posed by impacts on Earth. Our collaboration with NASA's Jet Propulsion Laboratory (JPL) and the utilization of their experiments will enhance the community's basic understanding of lunar materials as we delve into the development of a new material model. It I simportant to note, however, that the work conducted to couple our two advanced numerical methods (FDEM/SEM) is directly relevant to the DOE/NNSA mission of Remote Sensing for Nuclear Non-Proliferation mission space in that these advancements will be directly applicable to our nuclear explosion monitoring research.

Publications/Presentations:

1. *Bozdag, E., Y.Ruan, N.n Metthez, A. Khan, K. Leng, M. van Driel, M. Wieczorek, A. Rivoldini, C. S. Larmat, D. Giardini, J. Tromp, P. Lognonné, and W. B. Banerdt.(2017), Simulations of Seismic Wave Propagation on Mars, Space Science Reviews, 211(1-4), 571–594, doi:10.1007/s11214-017-0350-z.*
2. Karakostas, F., V. Rakoto, P. Lognonné, C. S. Larmat, I. J. Daubar, and K. Miljković (2018), Inversion of Meteor Rayleigh Waves on Earth and Modeling of Air Coupled Rayleigh Waves on Mars, Space Science Reviews, 214(8), doi:10.1007/s11214-018-0566-6.

Financial Impacts:

We got $500k from the Department of Defense (Defense Threat Reduction Agency) in 2018 for a collaborative Targeting Analysis. In 2019, we got $550 from NASA for modeling the effect of the Mars Lander Project, and $600k from the DOE LANL X-division for threat reduction. Work conducted under the LDRD-ER has led to a code development effort for HOSS to conduct cratering analysis relevant to the LDRD program as well as the follow-up project with DTRA.

Supporting Viewgraphs:

Please find attached ppt file.